Automated Nutrient Solution Control System using Embedded Fuzzy Logic Controller for Smart Nutrient Film Technique Aquaponics

Ronnie S. Concepcion II, Sandy C. Lauguico, Pocholo James M. Loresco,
Ira C. Valenzuela, Elmer P. Dadios, and Argel A. Bandala

***Abstract*—Nutrient imbalance occurs in a recirculating aquaponic system due to constant absorption of plants set on the growth bed. Biological parameters nutrient solution system is usually affected by pH and electrical conductivity which are vital to plant health, thus, necessary to be monitored and controlled. To address this problem, the development of an automated biological information control system using fuzzy logic for smart aquaponics is deened necessary. This system is composed of two sections: the design of nutrient solution control system and the design of fuzzy logic that will control the solenoid valves for fluid distribution based on the levels of pH and electrical conductivity. Two valves mechanically control the inflow of pond water and concentrated water that is substantially fertilizer-dissolved water. The duration of having the solenoid valve open is based on the triggered membership function of the output of fuzzy controller. The fuzzy inference engine used the combined Min-Max and Mamdani methods. The centroid method was used for defuzzification. The embedded fuzzy logic library (eFLL) was deployed using Arduino microcontroller. The designed mechanism provides suitable decisions for the control system of aquaponics nutrient solution.**

***Keywords*—aquaponics, biosystems engineering, fuzzy logic controller, soilless agriculture, water nutrient solution**

Electronics and Communications Engineering, De La Salle University, Manila, Philippines (email: *ronnie_concepcionii@dlsu.edu.ph)

Manufacturing Engineering and Management, De La Salle University, Manila, Philippines

Electronics Engineering Department, Technological University of the Philippines, Manila, Philippines

I. Introduction

Aquaponics combines the science of aquaculture and hydroponics which provides a higher sustainability for the food production system [1]. It is an efficient technique of growing plants in soilless environment. Plant roots are submerged onto the flowing water with nutrients suitable for their growth. However, over time, the level of nutrients diminishes due to considerably continuous intake of plants. This nutrient solution system employs the core importance of aquaponics that may benefit or retard plant growth. Putting off the inappropriate number of nutrient limits the growth of plant. To improve high cultivation rate, precise control of appropriate time and water nutrient is necessary [2-3]. The different uptake rate of the plants must be considered as well. During warm weather, plants will take more water than the nutrient dissolved in the water and use it for transpiration. This process makes use of the excess water to evaporate and to cool down its own biological body thereby resulting to more concentrated nutrient solution.

Consequently, it is evident that modern approach like artificial intelligence deals to further enhance an automated control system. With automated water valve control system, correct level of water nutrients will be maintained in the system water flow.

The main objective of this study is to design an automated nutrient solution control system, particularly consisting of biological information of pH and electrical conductivity. This will help maintain the suitable nutrient level suitable for the plant being cultivated. Specifically, it aims to design a nutrient solution control system composed of solenoid water valves, water mixing tank and water pump; and to design the fuzzy logic controller that will regulate the amount of pond water and concentrated water coming into the water mixing tank. This study focuses on the use of fuzzy logic to regulate the suitable level of water biological parameters of pH and electrical conductivity in

Copyright © 2020 by De La Salle University

a nutrient mixture tank. The input parameters of the control system are pH and electrical conductivity levels. Meanwhile, the output of the system is the control of solenoid valves of pond water and concentrated water that are set as inflow to the nutrient mixture tank.

$$pH = -\text{LOG}[H^+]V_c = \frac{V_i(EC_f - EC_i)}{EC_u - EC_i}$$

II. METHODOLOGY

The methodological framework of the system is shown in Fig. 1 which consists of two phases, namely, design of nutrient solution control system and design of fuzzy logic controller.

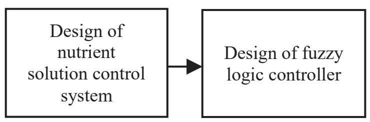

Fig. 1. Methodological framework of the control system

A. Nutrient Solution Control System

The design of nutrient solution control system deals with the realization of hierarchy of the system and design of its control process.

Based on Fig. 2, the hierarchical approach of the study is classified into two, namely, biological information and controller. Biological information is subdivided into pH and EC as its measured parameters. Each parameter has three indicating levels. The controller classification is proceeded by water valves as its output indicator.

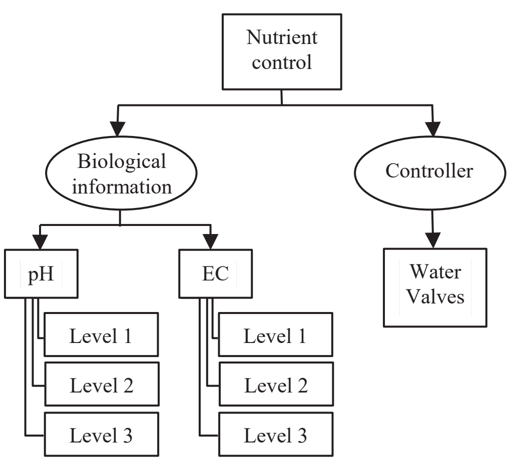

Fig. 2. Hierarchy of nutrient solution control system

Based on Fig. 3, the nutrient solution control system used solenoid valves (Valve 1 and Valve 2) for regulating the flow of pond water and concentrated water into the water mixing tank. When the plants set on the growth bed consumes nutrient water, the pH and EC level changes resulting to nutrient imbalance in the nutrient solution. The changing value of these biological parameters is due to the varying absorption of plants that is also affected by the weather. The nutrient system is controlled by the level of pH and EC parameters and the opening and closing of solenoid valves.

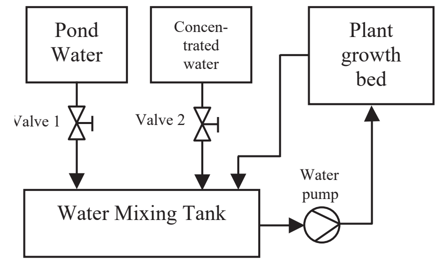

Fig. 3. Design of nutrient solution control system

B. Fuzzy Logic Controller

The design of fuzzy logic controller deals with linguistic fuzzy rules used to decide the intended control based on crisp inputs. Fuzzy logic system is an expert system that maps out crisp inputs. It is used to simulate knowledge by using a reason on human circumstances. The fuzzy logic implementation to control the solenoid valves of pond water and concentrated water tank is depicted in Fig. 4 with three major sections, namely, fuzzification, fuzzy rule-based evaluation and inference engine, and defuzzification.

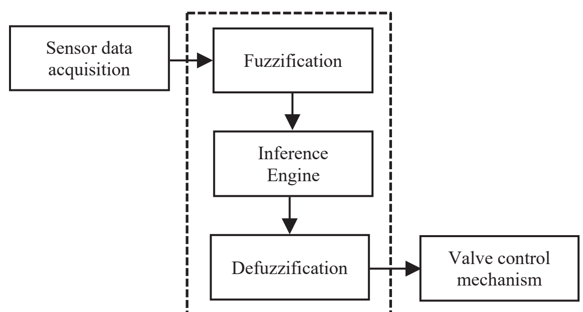

Fig. 4. Nutrient solution control system using fuzzy logic

The first step in fuzzy logic system is to determine the parameters involved in the process and define its fuzzification function. The crisp inputs include pH and EC concentrations on the nutrient mixture tank. The crisp output includes control of solenoid valves. The fuzzy sets using linguistic variables and term members are defined hereunder. Valve 1 relates to tank containing pond water and valve 2 to concentrated water.

phLevel (ph) = {low, normal, high}
ecLevel (ec) = {low, normal, high}
valve1Control (v1c) = {short, average, long}
valve2Control (v2c) = {short, average, long}

The second step was fuzzification which performs the mapping procedure to yield membership level. It estimated the membership value of fuzzy functions for input and output variables. Membership functions have features such as core, support and boundary that is mathematically defined in Eq. 2, 3 and 4 respectively. The core of a membership function in any fuzzy set, $\tilde{A}$ consists of all the elements of y that is technically 1. The support of a membership function is characterized by nonzero membership. The boundary of the membership function is characterized by incomplete nonzero membership in the whole membership set.

$$\mu_{\tilde{A}}(y) = 1 \quad (2)$$
$$\mu_{\tilde{A}}(y) > 0 \quad (3)$$
$$1 > \mu_{\tilde{A}}(y) > 0 \quad (4)$$

Fuzzification has two methods, namely, support fuzzification (s-fuzzification) method that is defined by Eq. 5; and the grade fuzzification (g-fuzzification) method which employs the inverse of s-fuzzification. The s-fuzzification was employed in this study.

$$\tilde{A} = \mu_1 Q(x_1) + \cdots + \mu_n Q(x_n)$$

In Eq. 5, $Q(x_n)$ is the kernel of fuzzification. The s-fuzzification emphasizes constant and the transformation of x_n to a fuzzy set.

The pH (x) parameter consists of three linguistic values, namely, low, normal and high, describing the acidic concentration of water in the nutrient mixture tank. Its membership functions are represented by mix of trapezoidal and triangular functions that are shown in Figure 5. The low, normal, and high membership functions for pH have degree of membership ranges of 0 to 6.0, 6.0 to 6.5 ppm and 6.6 to 14, respectively.

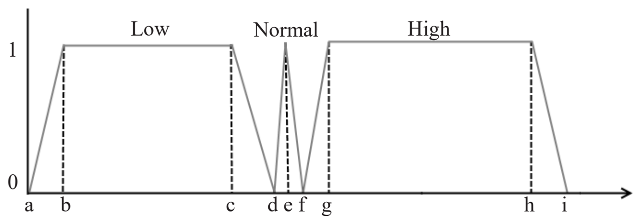

Fig. 5. Membership functions for pH

The value degree of memberships for pH input parameter are shown in Eq.6, 7 and 8.

$$\mu_{pH_{Low}} = \begin{cases} \frac{x-a}{b-a}, a \le b \\ 1, b \le c \\ \frac{d-x}{d-c}, c \le d \\ 0, a \le \ x \ge d \end{cases} \quad (6)$$

$$H_{Normal} = \begin{cases} \frac{x-d}{e-d}, d \le e \\ \frac{f-x}{f-e}, e \le f \\ 0, d \le x \ge f \end{cases} \quad (7)$$

$$\mu_{pH_{High}} = \begin{cases} \frac{x-f}{g-f}, f \le g \\ 1, g \le h \\ \frac{i-x}{i-h}, h \le i \\ 0, f \le x \ge i \end{cases} \quad (8)$$

The electrical conductivity (y) parameter consists of three linguistic values, namely, low, normal, and high, describing the electrical conductivity level of nutrient solution in the mixture tank. Its membership functions were represented by combination of trapezoidal and triangular functions that are shown in Fig. 6. The low, normal, and high membership functions for EC have degree of membership ranges of 0 to 0.8 mS/cm, 0.8 to 1.2 mS/cm and over 1.2 mS/cm, respectively.

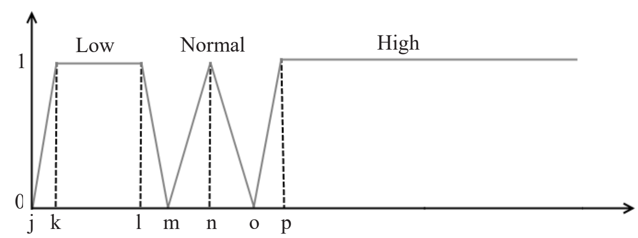

Fig. 6. Membership functions for EC

The value degree of memberships for EC input parameter are shown in Eq. 9, 10 and 11.

$$\mu_{ec_{Normal}} = \begin{cases} \frac{y-j}{k-j}, j \le k \\ 1, k \le l \\ \frac{m-y}{m-l}, l \le m \\ 0, j \le \ y \ge m \end{cases} \quad (9)$$

$$\mu_{ec_{High}} = \begin{cases} \frac{y-m}{n-m}, m \le n \\ \frac{o-y}{o-n}, n \le o \\ 0, m \le y \ge o \end{cases} \quad (10)$$

$$\mu_{ec_{Critical}} = \begin{cases} \frac{y-o}{p-o}, o \le p \\ 1, y \ge p \\ 0, y \le o \end{cases} \quad (11)$$

The outputs of fuzzy logic controller are valve1Control and valve2Control (z) which consists of three linguistic values, namely, short, average and long, describing the time duration in minutes of solenoid valves in open state. The membership functions for vc1 and vc2 were represented by triangular functions as shown in Figure 7. The short, average and long duration membership functions for solenoid valves 1 and 2 control have degree of membership ranges of 0 to 1 minute, 0.75 minute to 1.25 minute, 1.25 to 1.75 minute, respectively.

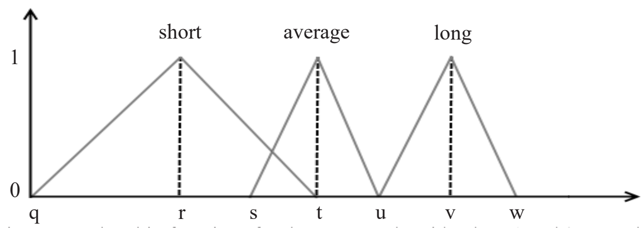

Fig. 7. Membership functions for the output solenoid valves 1 and 2 control

The value degree of memberships for v1c and v2c output parameters are shown in Eq. 12, 13 and 14.

$$\mu_{v1c_{short}} = \mu_{v2c_{short}} = \begin{cases} \frac{z-q}{r-q}, q \le z \le r \\ \frac{t-z}{t-r}, r \le z \le t \\ 0, q \le z \ge t \end{cases} \quad (12)$$

$$\mu_{v1c_{average}} = \mu_{v2c_{average}} = \begin{cases} \frac{z-s}{t-s}, s \le z \le t \\ \frac{u-z}{u-t}, t \le z \le u \\ 0, s \le z \ge u \end{cases} \quad (13)$$

$$\mu_{v1c_{long}} = \mu_{v2c_{long}} = \begin{cases} \frac{z-u}{v-u}, u \le z \le v \\ \frac{w-z}{w-v}, v \le z \le w \\ 0, u \le z \ge w \end{cases} \quad (14)$$

The third step was the employment of fuzzy inference system which dealt with the construction of linguistic rules that provides solution variable to each fuzzy rule as shown in Table 1. It has two different inputs, pH and EC, and has three membership degrees resulting to nine possible outputs. Table 1 defines the IF-THEN principle of fuzzy logic rules using the AND operator for both inputs and outputs. Rule 1 states that IF pH is Low AND EC is low, THEN Valve1 is Long AND Valve2 is Long.

The hybrid Max-Min and Mamdani technique was employed in this study in determining the value of each fuzzy rule based on combining the fuzzy rule strength with the output membership function. The resulting Mamdani inference system, x^*, is defined by Eq. 15.

$$x^* = \frac{\sum_{i=1}^{n} \overline{x_i}}{n} \quad (15)$$

TABLE 1
Fuzzy Rules for Nutrient Solution Control System

Rule	If		Then	
	pH	EC	Valve1	Valve2
1	Low	Low	Long	Long
2	Low	Normal	Long	Average
3	Low	High	Long	Short
4	Normal	Low	Average	Long
5	Normal	Normal	Average	Average
6	Normal	High	Average	Short
7	High	Low	Short	Long
8	High	Normal	Short	Average
9	High	High	Short	Short

The fourth step was defuzzification which translates the fuzzy set results of fuzzy inference engine into crisp values. The centroid method defined by Eq. 16 was employed.

$$X = \frac{\int \tilde{\mu}_A(x) \cdot x dx}{\int \tilde{\mu}_A(x) \cdot dx} \quad (16)$$

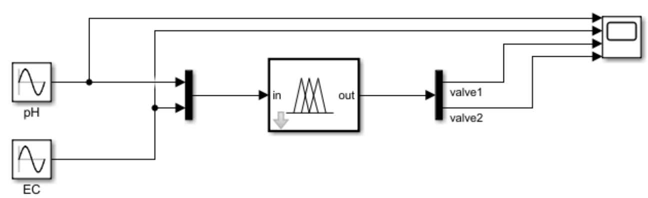

Fig. 8. Simulink diagram for pH and EC based nutrient solution control system

Fig. 8 shows the summing step in testing the developed fuzzy logic controller with pH and EC crisp inputs and valve controls as outputs. The pH value was generated using a sine wave generator with amplitude of 14, bias of 7 and frequency of 1 rad/sec. The EC value was generated using a sine wave with amplitude of 10, bias of 5 and frequency of 5 rad/sec. These two inputs were set into multiplexer then to the fuzzy logic controller for valve control. A demultiplexer was used to split the output into two, one for each valve.

III. Results and Discussion

A. Water Sources for Nutrient Solution System

Plants intake nutrients from nutrient-dissolved water. There are thirteen recorded mineral nutrients that is collectively set for plant growth which comes from water sources. These mineral nutrients are classified into macronutrients and micronutrients. The latter one is considered essential for plant growth consisting of boron, copper, iron, chloride, manganese, molybdenum and zinc. These nutrients are present in differing concentrations in water sources such as ground water, pond water and concentrated water [4].

Ground water is a reliable source of water as it comes from cracks between rocks, and spaces in the bodies of soil bed. Globally, 60 % of ground water is utilized in irrigation system [5-6]. Pond water, technically, comes from naturally or artificially constructed water basin area that is different from river because it has no moving water in it. Ponds promotes biota cultivation. Fish effluents serve as organic fertilizer for plants in recirculating system. It is rich in macronutrients such as compounds of nitrogen and phosphorus that is required for good plant health. The pond water used in a recirculating aquaponics system loses its nutrients after the plants have naturally filtered it [7]. With pond water, the hydroponics-prone plant disease called pythium which rots the root of plants is eliminated because of the participation of microbes. These microbes are nitrifying bacteria responsible for converting fish effluents into organic plant fertilizer that provides no harm to water-submerged plant roots [8]. Concentrated water is substantially nutrient-dissolved water by applying natural and synthetic fertilizers. Subsequently, the property of water is constantly changing due to external altering factors of weather and biotic actions. Addition of fertilizer will enhance the balance of nutrient dissolved in the water. As with soil cultivation, aquaponics can also be damaged by over fertilization resulting to burning of roots and nutrient imbalances [4].

B. Biological Information of Water

Stressor, exposure and response indicators are the basis of measurement of the U.S. Environmental Protection Agency pursuing the Environmental Monitoring and Assessment Program in understanding the biological, radiological, and physical information of water. Biological information constitutes dissolved oxygen, ammonia, nitrogen, potential of hydrogen (pH), electrical conductivity (EC), and heavy metals [9]. Any water sources in irrigation system can be easily characterized by measuring its pH and EC. These parameters can vary significantly due to climate change, bedrock settlement, and biota from which plants are included [10].

The pH information expresses the hydrogen ion concentration or acidity of water and is defined by Eq. 1 with brackets symbolizing as concentration. Higher [H+] and lower [H+] corresponds low and high pH respectively.

$$pH = -\log[H^+] \tag{1}$$

The EC information expresses the ability of water to conduct electricity through it with strength based on the dissolved materials on it. The unit that corresponds to EC is Siemens per unit area. The higher the dissolved materials, particularly of salts that belongs to ionic species, in an aqueous solution resembles higher ion concentration, thus, higher EC level. The level of EC can verify if the nutrient solution lost its nutrients. If it measures high value, it means that additional water must be added to level the original value. Mathematically, EC is defined by Eq. 2 as the ratio of current density, J, and electric field intensity, e. It is also inversely proportional with resistivity, r.

$$s = \frac{J}{e} = \frac{1}{r} \tag{2}$$

The suitable values of pH and EC for lettuce is 6.0 to 6.5 and 0.8 to 1.2 [11-12]. The required pH level for lettuce is the same with cauliflower and broccoli and is significantly higher than tomato and carrot. The required EC level for lettuce is comparably lower than cauliflower, cabbage, broccoli, carrot, cucumber and tomato.

C. Nutrient Solution System

Aquaponics system solely rely in water flow system in providing food for plants. It supplies nutrients and minerals in the flowing water source. Management of water quality is of objective to provide suitable nutrients for plants. Enhancement of poor water quality, specifically ground water, must be implemented [13]. Salinity, dissolved solids and pathogens are present in untreated water which must be eliminated and balanced out accordingly. For intolerant plants such as lettuce, high level of iron and sodium can cause iron scale. In that case, mixing of different aqueous medium is critical.

An automated scheduling for water source with flow control system using Arduino and DS3231 real time clock was developed to solve water shortage and optimize ground water and pond water sources. Fertigation system was also implemented. The fertigation system injects fertilizer-dissolved water to the system once a week when ground water and pond water valves are close. Ground water valve is open four times a week when pond water and fertigation system is close. Pond water valve is open twice a week when all other valves are close [4].

A control system for hydroponics nutrient solution was made using Protégé software. It has web-based functions that employs the principal response capability of the web ontology language (OWL) and resource description framework (RDF). The parameters EC, pH, intensity of solution and plant species are set as inputs for decisions in control. The flow of two solutions contained in tanks A and B are controlled by opening and closing the valves based on the ontological relation of tools and system variables [3]. The volume of concentrated nutrient solution (V_c) used to increase the level of EC in the nutrient solution tank is mathematically defined by Eq. 3. The parameters V_i is the volume of the system nutrient solution before the addition of V_c, EC_u is the EC value of the concentrated solution to be added into the nutrient solution, EC_i is the EC value of the nutrient solution before the addition of V_c, and EC_f is the EC value of the nutrient solution after the addition of V_c.

$$V_c = \frac{V_i(EC_f - EC_i)}{EC_u - EC_i} \quad (3)$$

Fuzzy logic control was employed in several studies including the control of solution valve in ebb and flow hydroponics system based on temperature and moisture parameters [14-15]; control of four tanks of alkaline solutions, acid solutions, mixture of alkaline and acid solutions, and fertimix based on proportional small-scale process [16-18]; control of heater and solution tank valve based on temperature and pH level of water with wireless data login [19]; and system control based on pH, electro conductivity and water temperature with remote monitoring [20]. Automated pH controller system for deep water culture (DWC) hydroponic cultivation was made by adjusting the pH solution valve. This technique automatically increases and decreases the pH level of water by a factor of 0.58 and 1.15 respectively [21].

However, estimation of pH and EC, and automatic control system for same biological parameters were materialized using linear regression algorithm. Three variables were used, namely, EC or pH for input, nutrient solution or nitric acid for control process, and target as output [22-23].

Shown in Fig. 9 to 12 are the curves obtained using fuzzy logic-based nutrient solution valve control system. There is transition for pH with level 5 to 6.5 in Valve1 from 1.5 to 0.5 minute at open state. The duration of Valve2 increases from 0.5 to 1 minute in pH value of 5 to 6 and decreases from 1 to 0.5 minute in pH value of 6 to 7. The duration of Valve1 in open state decreases from 1 to 0.5 minute for EC level of 0 to 0.8. It remains in 0.5-minute level for any increase in EC. Valve2 operates in 1 to 1.5 minute-duration for EC levels of 0 to 0.8 and decreases from 1.5 to 0.5 minute for EC levels of 0.8 to 1.2.

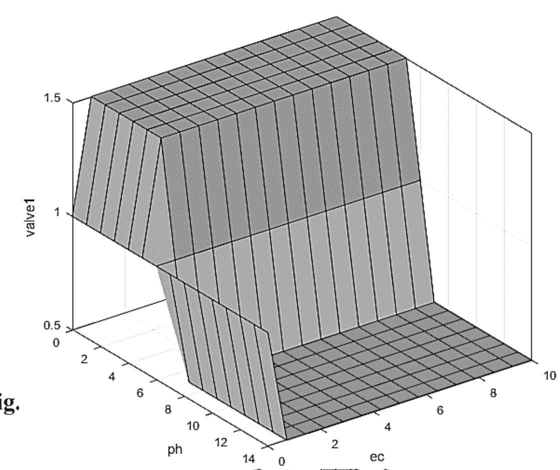

Fig.

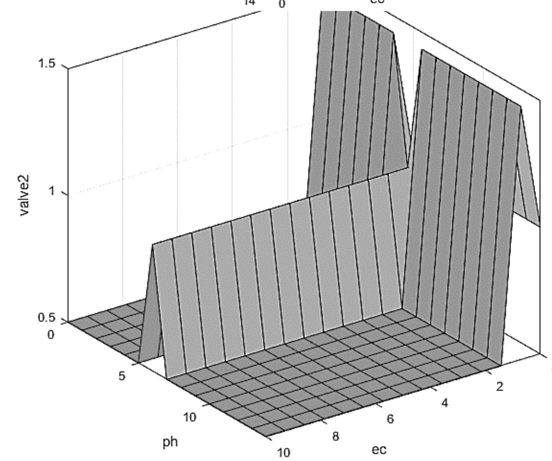

Fig. 10. Valve2 state based on pH and EC inputs

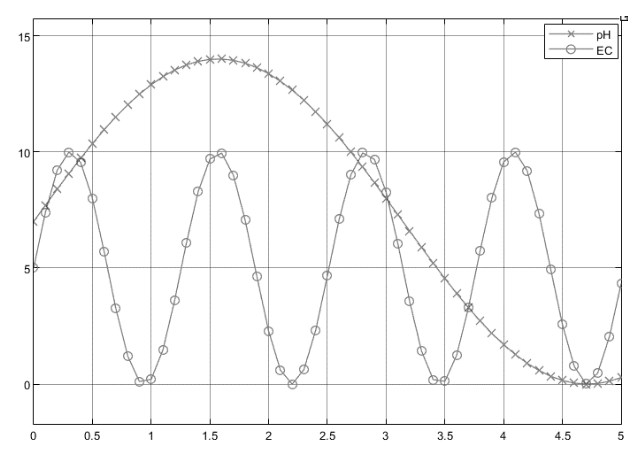

Fig. 11. Valve1 and Valve2 states based on pH and EC inputs (y-axis)

Fig. 11 shows the input pH and EC parameters set using sine wave. It corresponds the combination of possible values of the crisp input. For time step 1.5, the pH level is at maximum 14 and the EC level is 9. These levels are coequal to High AND High linguistic variables. Based on Fig. 12, on time step 0.5, both values of valve1 and valve2 are set on 1-minute or Short duration. For time step 3.2, the pH level is 6.5 and EC level is 4, which corresponds to Normal AND High linguistic variables. The corresponding duration of valves 1 and 2 are set both in Average duration of 1 minute. For time step 4, the pH is 2 and EC is 9, which are Low AND High on its linguistic form. Valves 1 and 2 are controlled in 1.5 and 0.5 minute-durations, respectively, as designed with linguistic variables of Long AND Short. For time step 4.7, both pH and EC are considerably 0 or Low level. The corresponding crisp output is both 1.5 minute or Long linguistic variable.

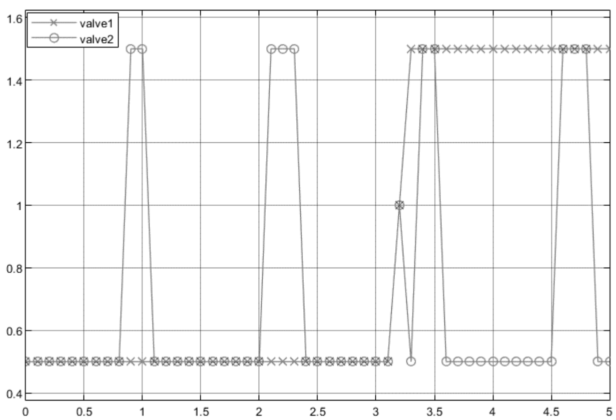

Fig. 12. Valve1 and Valve 2 states based on time duration (y-axis)

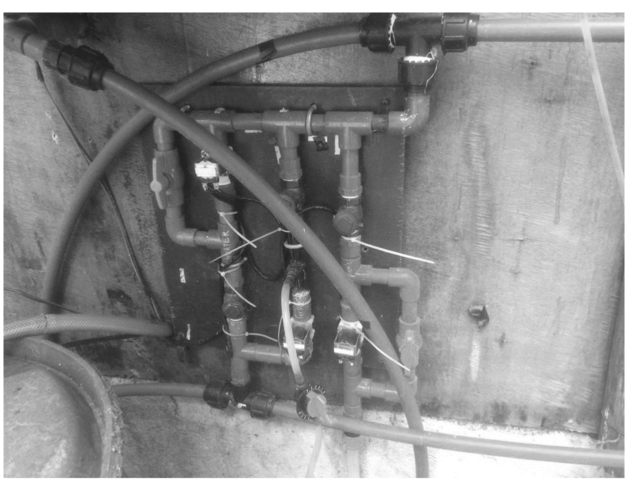

Fig. 13. Actual pipe connections

Fig. 13 shows the actual connection of water pipes used in nutrient solution control for hydroponics chamber of the aquaponics system. One-way valves were inserted in the connection to assure that there will be only one flow of fluid in a specific direction when the solenoid valves of fluid sources namely, pond water and concentrated water were open. Solenoid valves were controlled using Arduino microcontroller with embedded fuzzy logic library (eFLL).

IV. Conclusion and Recommendation

This study introduced an expert system for providing a fuzzy classification approach in controlling the valves of pond water and concentrated water tanks for regulating the level of pH and EC in nutrient mixture tank. Through fuzzy logic, the designed intelligent system was able to decide what duration will be set on output solenoid valves as to its open state. In this manner, the suitable nutrient balance was maintained that is necessary for healthy plant growth.

The designed fuzzy logic controller was implemented in a smart farm cultivating lettuce. For further research related to this study, addition of solution tank containing pure water may be considered.

Acknowledgment

The researcher would like to thank the Engineering Research and Development Technology (ERDT) and the De La Salle University (DLSU) Intelligent Systems Laboratory for the support they provided.

References

[1] Trang, N. and Brix, H., (2014). Use of planted biofilter in integrated recirculating aquaculture-hydroponics systems in the Mekong Delta Vietnam. Aquac. Res. 45 (3), 60-469.

[2] Izumi, R., Ono, A., Ishizuka, H. et al., (2017). Biological information (ph/ec) sensor device for quantitatively monitoring plant health conditions. Proceedings of IEEE Sensors.

[3] Phutthisathian, A., Pantasen N. et al., (2011). Ontology-based nutrient solution control system of hydroponics. Proceedings - 2011 International Conference on Instrumentation, Measurement, Computer, Communication and Control, IMCCC 2011.

[4] C. Dinio, N. Paragon, G. Peleña et al., (2018). Automated water source scheduling system with flow control system. IEEE HNICEM.

[5] Yanes, A. R., Martinez, P., & Ahmad, R. (2020). Towards automated aquaponics: A review on monitoring, IoT, and smart systems. Journal of Cleaner Production, 121571. doi:10.1016/j.jclepro.2020.121571

[6] Incrocci, L., Thompson, R. B., Fernandez-Fernandez, M. D., De Pascale, S., Pardossi, A., Stanghellini, C., Gallardo, M. (2020). Irrigation management of European greenhouse vegetable crops. Agricultural Water Management, 242, 106393. doi:10.1016/j.agwat.2020.106393

[7] Yang, T., & Kim, H.-J. (2020). Comparisons of nitrogen and phosphorus mass balance for tomato-, basil-, and lettuce-

based aquaponic and hydroponic systems. Journal of Cleaner Production, 122619. doi:10.1016/j.jclepro.2020.122619

[8] Oliveira, V., Martins, P., Marques, B., Cleary, D. F. R., Lillebø, A. I., & Calado, R. (2020). Aquaponics using a fish farm effluent shifts bacterial communities profile in halophytes rhizosphere and endosphere. Scientific Reports, 10(1). doi:10.1038/s41598-020-66093-8

[9] Fierro-Sañudo, J. F., Rodríguez-Montes de Oca, G. A., & Páez-Osuna, F. (2020). Co-culture of shrimp with commercially important plants: a review. Reviews in Aquaculture. doi:10.1111/raq.12441

[10] Bruckner, M., (2018). Water and soil characterization – pH and electrical conductivity. Microbial Life Educational Resources. Montana State University, Bozeman.

[11] Deshpande, P., Abraham, A., Iyer, B., & Ma, K. (Eds.). (2021). Next Generation Information Processing System. Advances in Intelligent Systems and Computing. doi:10.1007/978-981-15-4851-2

[12] El-Nakhel, Giordano, Pannico, Carillo, Fusco, Pascale, & Rouphael. (2019). Cultivar-Specific Performance and Qualitative Descriptors for Butterhead Salanova Lettuce Produced in Closed Soilless Cultivation as a Candidate Salad Crop for Human Life Support in Space. Life, 9(3), 61. doi:10.3390/life9030061

[13] Williams Ayarna, A., Tsukagoshi, S., Oduro Nkansah, G., Lu, N., & Maeda, K. (2020). Evaluation of Tropical Tomato for Growth, Yield, Nutrient, and Water Use Efficiency in Recirculating Hydroponic System. Agriculture, 10(7), 252. doi:10.3390/agriculture10070252

[14] M. Daud, V. Handika and A. Bintoro, (2018). Design and realization of fuzzy logic for ebb and flow hydroponic system. International Journal of Scientific & Technology Research.

[15] Wang, W., Jia, Y., Cai, K., & Yu, W. (2020). An Aquaponics System Design for Computational Intelligence Teaching. IEEE Access, 1–1. doi:10.1109/access.2020.2976956

[16] D. Yolanda, H. Hindersah, F. Hadiatna et al., (2017). Implementation of real-time fuzzy logic control for NFT-based hydroponic system on Internet of Things environment. Proceedings of the 2016 6th International Conference on System Engineering and Technology, ICSET.

[17] Wei, Y., Li, W., An, D., Li, D., Jiao, Y., & Wei, Q. (2019). Equipment and Intelligent Control System in Aquaponics: A Review. IEEE Access, 1–1. doi:10.1109/access.2019.2953491

[18] Farooq, M.S.; Riaz, S.; Abid, A.; Umer, T.; Zikria, Y.B. (2020). Role of IoT Technology in Agriculture: A Systematic Literature Review. Electronics 2020, 9, 319.

[19] M. Mamatha and S. Namratha, (2017). Design and implementation of indoor farming using automated aquaponic system. IEEE International Conference on Smart Technologies and Management for Computing, Communication, Controls, Energy and Materials, ICSTM.

[20] B. Siregar, S. Efendi, H. Pranoto et al., (2018). Remote monitoring system for hydroponic planting media. International Conference on ICT for Smart Society, ICISS.

[21] T. Kaewwiset and T. Yooyativong, (2017). Estimation of electrical conductivity and pH in hydroponic nutrient mixing system using Linear Regression algorithm. 2nd Joint International Conference on Digital Arts, Media and Technology 2017: Digital Economy for Sustainable Growth, ICDAMT.

[22] T. Kaewwiset and T. Yooyativong, (2017). Electrical conductivity and pH adjusting system for hydroponics by using linear regression. ECTI-CON 14th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology.

[23] M. Saaid, A. Sanuddin, M. Ali et al., (2015). Automated pH controller system for hydroponic cultivation. IEEE Symposium on Computer Applications and Industrial Electronics.